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EVOLUTION OF POWER SUPPLY AND ITS APPLICATION TO ELECTRICAL AND ELECTRONIC DEVICES: AN ANALYSIS

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ABSTRACT

Electricity can be produced using chemical effect where the movement of ions constitutes a flow of current through the electrolyte. Electrochemical cells are used as storage cells where chemical energy can be converted into electrical energy. The most efficient and widely used method for the generation of electricity is based on the laws of Electromagnetic Induction. According to this law electromotive force is induced in a conductor whenever the conductor cuts across magnetic lines of flux. The invention of the Diode Valve in 1904 and the invention of the triode valve in 1906 and their large-scale production from 1920 onwards helped to manufacture electronic products and instruments. The invention of the galena-based Cat's whisker detector in 1906 was the milestone of manufacturing crystal radio receivers. Cuprous oxide rectifier was invented in 1926 and was used for the rectification of power supply frequencies. Selenium rectifier was invented in 1933 and it was also used for the rectification of power frequencies but selenium rectifier was more efficient and was best in low-voltage, heavy current applications. Commercial manufacturing of germanium crystal diode was started in 1946. Then invention of the bipolar junction transistor in 1948 had replaced the valves because of low power, low cost, small size and long-lasting. Electrical products are generally operated from the mains power supply. But electronic products are operated by D.C supply and nowadays most of the communication devices are designed to be operated by the low-watt power supply. Scientists and researchers are developing low power, low heat dissipation, low dropout, miniature and energy harvesting efficient power supply.

Key words: Capacitance, Magnetic Flux, Power Supply, Rectifier, Transformer, Voltage Regulation

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1. INTRODUCTION

Michael Faraday an English Scientist formulated the basic law of Electromagnetic Induction in 1831. According to Faraday's Law, whenever any magnetic flux linked with a coil changes an e.m.f is induced in the coil and the magnitude of the induced e.m.f is e = N $\frac{d\Phi}{dt}$, where, N= number of turns in the coil, and $d\Phi$ = change in flux [1]. The induced e.m.f is also represented by e = − N $\frac{d\Phi}{dt}$, as the coil resists a change in magnetic flux by producing opposite voltage/current.

On the basis of Faraday's law electric motors, transformers, relays, etc. have been designed and produced. Thomas Davenport of Vermont State of USA constructed the first official battery-powered motor in 1834. Electric motors were not widely used during that time and after a long period of time in1886, William Sturgeon invented the first D.C motor suitable for industrial application. Relay, an electrically operated switch was invented in 1835 by an American Scientist Joseph Henry. Relay can be either switched on or off using the property of electromagnetic induction. The relay is used to regulate the power supply of various electrical and electronic gadgets and is used in the industry as well as in many consumer electronic products.

Applying Faraday's law William Stanley Jr. an American Physicist developed commercial transformer in 1886. A transformer is a device that transfers electrical power from one circuit to another circuit without any change of frequency. Using the property of mutual induction, electrical energy is transferred from the primary coil of a transformer to the secondary coil of the transformer. The r.m.s value of induced e.m.f in the secondary coil mainly depends upon the number of turns in primary and secondary windings of the transformer.

For the electronic devices, the D.C power of required voltage is converted from the A.C mains power supply inside the electronic devices by using an appropriate rectifier circuit or the required D.C power is available from the external power supply unit. Low power electronic devices like radio, tape recorder etc. are operated using battery cells as well as from the external electrical power supply source. The mains power supply can be directly connected with the low power electronic devices where the low power converter circuit is available as built-in inside the devices or the devices can be operated using an external low voltage power supply. The low voltage power supply was commonly known as Battery Eliminator [2] and was used widely in the earlier days for operating low power devices. The television receiver sets were operated from the A.C mains power supply or from the D.C mains power supply because for many years and even in the decade of 1980 and 1990, the mains power supply was D.C in many households. So, some television sets were designed to be operated using both the A.C and D.C power supply. For the pure A.C models, transformers were used in the power supply section and from the secondary windings of the transformer high and low voltages were produced as per the requirement of various sections of a T.V receiver.

For the A.C cum D.C models, there was no power supply transformer. The diode was used for the rectification of A.C to D.C and then several high-watts wire wound resistors were used for the appropriate power supply at different sections. Later on in the decade of 1970 switched mode power supply (SMPS) was introduced. The main conventional power supply transformer was not used in the switch mode power circuit. Without having A.C main power transformer, TV receivers based on SMPS circuits cab be designed to be operated either in A.C or D.C power supply. A very small and low weight switching transformer is used in the blocking oscillator [3] section of the SMPS circuit. The output D.C voltage is controlled in SMPS circuit according to the switching frequency and the duty cycle of the pulse width modulator circuit. SMPS is small, low weight, low cost and provides highly regulated power supply. Nowadays various energy harvesting systems are also used for low power devices.

2. SIMPLE POWER SUPPLY WITH OVER VOLTAGE PROTECTION USING RELAY AND TRANSFORMER

Using a transformer having multiple secondary windings and relay, a simple power supply circuit with over voltage protection can be made when input power supply voltage varies at different levels.

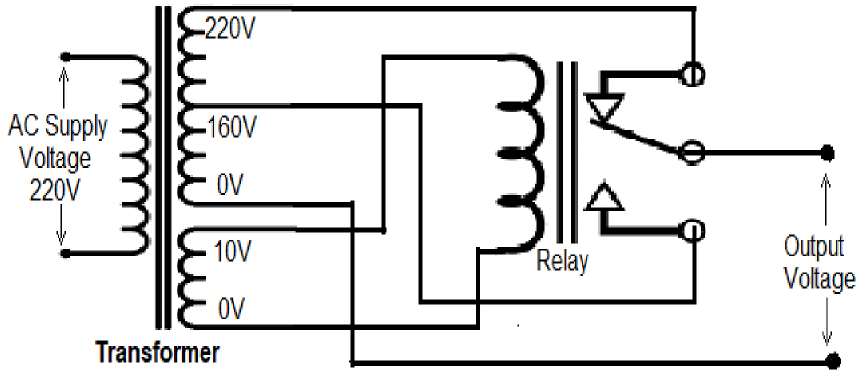

Figure 1 Diagram of Power Supply regulation with a Transformer and Relay

Here 12V relay has been used in the circuit diagram as shown in Fig.1. The relay is normally connected to the 220V secondary line of the transformer. When the A.C supply voltage is 220V, then the coil voltage of the relay is approximately 10V. In this condition, output voltage will be available from the 220V secondary line of the transformer and the relay is in the normally connected status.

When by any reason supply voltage will increase, then the voltage applied to the coil of the relay will also increase. When supply voltage will increase to 260V, then applied voltage to the coil of the relay will also increase to about 12V and the relay will be switched to the normally open state. Now the output voltage line will be connected to the 160V line of the transformer. Since supply voltage has increased to 260V, the output voltage of the 160V line of the transformer will also increase to 200V which is sufficient for the normal operation of electrical devices/gadgets. The input and corresponding output voltages are shown in Table 1.

Table 1 Input Supply Voltage and Output Voltage Relation

Supply Voltage (V)	Output Voltage (V)
200	200
220	220
240	240
250	250
260	200 (switching of relay)
280	220
300	240

John Ambrose Fleming an English Physicist invented the Vacuum Tube which is a Thermionic Valve in 1904. The simple Vacuum Tube contains a heated electron-emitted cathode and anode [4]. The electrons can flow from the cathode to the anode of the valve. This Vacuum Tube can be used as a rectifier i.e. to convert alternating current to direct current. Lee De Forest, an American Inventor added a third electrode called grid to Fleming's diode valve in 1906 and constructed a triode valve. A full wave rectifier circuit using diode valve is shown in Fig. 2 below.

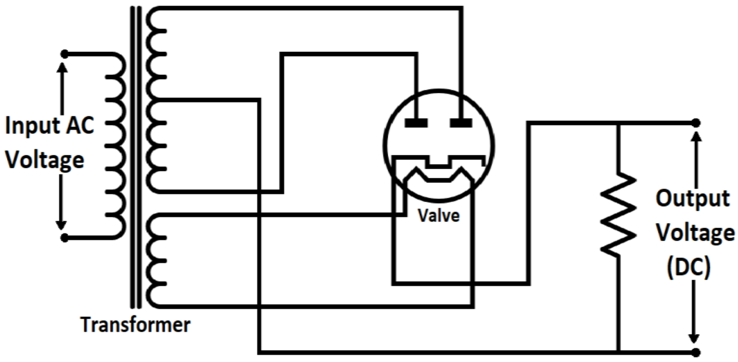

Figure 2 Diagram of Full wave Rectification Circuit using Diode Valve

Early valves used directly heated cathodes. Later, by inserting separate filaments, indirectly heated cathode valves were developed. Indirectly heated cathode valves eliminate unwanted A.C noise associated with the directly heated cathode valve. Triode valve was capable of amplification of signal and using this amplification feature Sperheterodyne Radio Receivers were developed. Gradually Television Receivers and Computers were developed using the valves as the key component. The invention of diode and triode valves was a pioneering invention in the field of Electronics and Computer Technology. From 1920 onwards, a vast quantity of valves was produced for Consumer Electronics, Industrial Electronics and also for the Defence System.

2.1. Cat's Whisker Crystal Detector

Two types of diodes were developed in parallel by scientists and engineers. One is a vacuum tube diode and the other is solid state diode.

Cat's whisker crystal detector was developed by using mineral crystal galena in 1906. Galena [5] is a semiconductor with a small band gap of about 0.4 eV. Cat's whisker crystal detector was basically used in the crystal radio receivers.

The operation of Cat's whisker crystal detector depends on the pressure created at the point of contact between a thin metal wire and a semiconductor crystal. Cat's whisker detector was also the earliest version of Schottky barrier diode where a point of contact-junction was formed between a metal and a semiconductor. Having a very low voltage drop between 0.15V to 0.45V and fast switching action, Cat's whisker crystal diode was used to rectify the radio frequency signal (containing with the audio signal) to a pulsating D.C waveform. The basic diagram of a Cat's whisker crystal detector is shown in Fig. 3. The disadvantage of the Cat's whisker detector was the requirement of manual adjustment to identify the sensitive hot spot on the crystal surface for the best detection of radio waves.

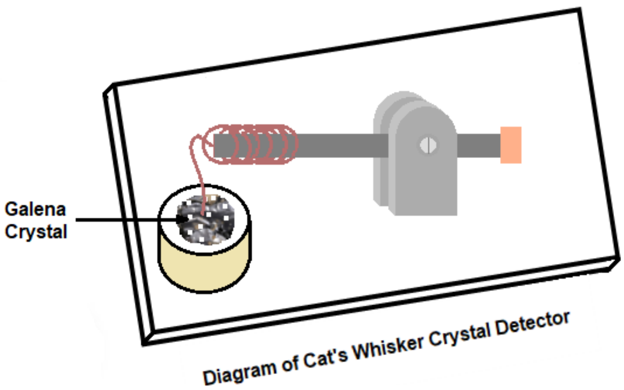

Figure 3 Basic diagram of a Cat's Whisker Crystal Detector

2.2. Crystal Radio Receiver

Cat's whisker crystal detector was the key component in the crystal radio sets. The other two basic components of the crystal radio sets were variable inductance coil and variable capacitance for making a tuning circuit whose function is to select a specific channel of a transmitting station. This crystal set does not require external power but requires a long aerial. The demodulated audio signal could be heard by using a high impedance earphone connected with a low value capacitance of about 0.001 microfarads in parallel. This low value capacitor was used to filter out the high frequency carrier wave from the baseband signal as shown in Fig. 4. Even the variable capacitance which is connected with the inductance may be excluded by using a sufficiently long external antenna according to the signal strength of the local transmitting station. The long antenna has also self capacitance and in that case the capacitance of the long antenna is used as a substitute for the variable capacitance [6].

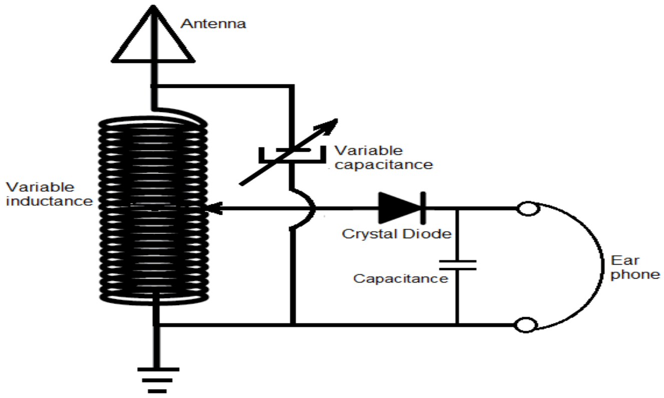

Figure 4 Simple diagram of a Crystal Radio Receiver

Diode valves were also used for the detection of radio frequency signals in the early period of the 20th century. Then commercial germanium crystal diode was launched in the market in the year 1946 and replaced the Cat's whisker crystal detector and reduced the use of valves for radio frequency signal detection.

3. THE CUPROUS OXIDE RECTIFIER (METAL RECTIFIER)

The cuprous oxide rectifier was invented in the year 1926 and was widely used for the rectification of A.C power in electronic devices including measuring instruments. The Cuprous oxide rectifier was not suitable for the detection of radio frequency currents, because of its high capacitance per unit area. In the cuprous oxide rectifier as shown in Fig. 5, the barrier layer lies between the copper and the oxide, and the contact with the oxide is made by a lead disc [7].

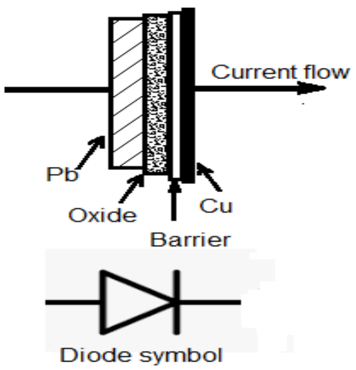

Figure 5 Construction of Cuprous Oxide rectifier with Diode symbol

3.1. Selenium Rectifier

Selenium rectifier is a metal diode and also called as metal rectifier. The original term was rectifier and renamed as a diode in 1919. The selenium rectifier was invented in 1933. The stacks of selenium rectifier consisted of selenium cells as shown in Fig. 6. The selenium diode was used to convert high alternating current (A.C) to direct current (D.C). The disadvantages of selenium rectifiers are higher voltage drop across the selenium plates, reducing life expectancy for high operating voltage & current, effects of temperature etc.

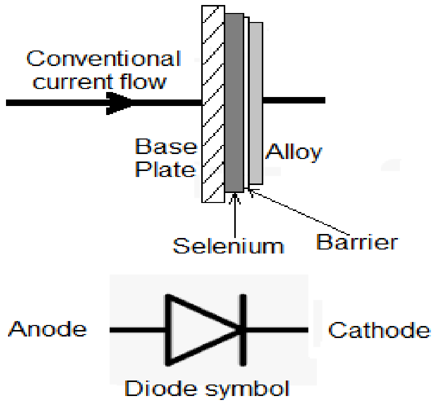

Figure 6 Selenium Metal Rectifier construction and Diode Symbol

Nowadays silicon diode is widely used in lieu of selenium diode. In the selenium rectifier, there are generally five-colored connection points; two yellow points for supply from transformer secondary, one red point for positive output and two black points are connected together as ground. The full wave bridge rectifier circuit using selenium diode has been shown in Fig. 7.

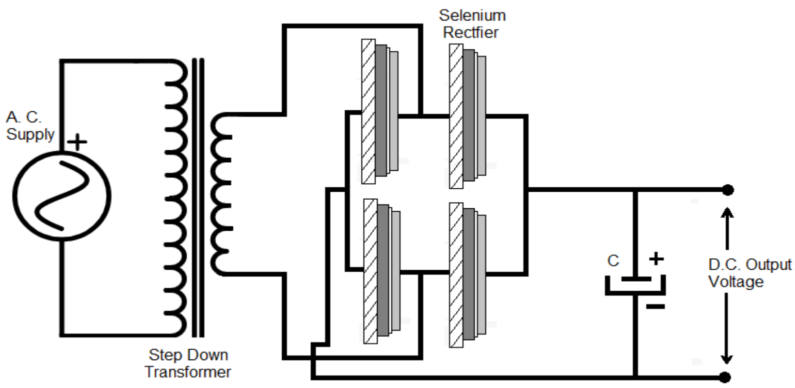

Figure 7 Full Wave Bridge Rectification using Selenium Rectifier

3.2. P-type and N-type Semiconductor

By adding a small number of impurities to a pure semiconductor like germanium or silicon, P-type or N-type semiconductor can be formed. By adding trivalent atoms we can make P-type semiconductors and by adding pentavalent atoms we can make N-type semiconductors [8]. Silicon is preferred over germanium because of its low cost, high reverse breakdown voltage, very small reverse leakage current, ability to withstand higher temperature etc. Nowadays N-type semiconductors are extensively used than P-type semiconductors because the conductivity of N-type semiconductors is more than that of P-type semiconductors.

3.3. P-N Junction

There is a greater concentration of holes in the P-side and a greater concentration of electrons in the N-side. Due to this variation of concentrations, the holes from the P-side diffuse to the N-side and combine with the electrons. Similarly, the electrons from the N-side diffuse to the P-side and combine with the holes. This combination of holes and electrons produces a narrow region at the junction and this narrow region is called depletion region as shown in Fig. 8.

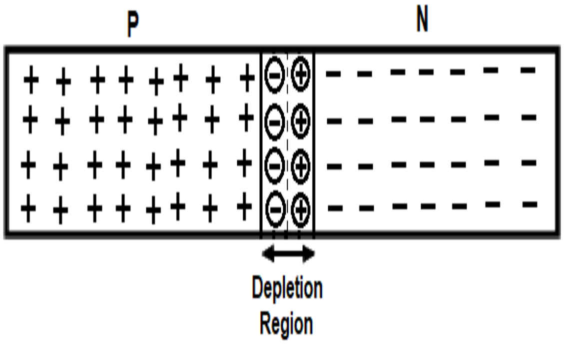

Figure 8 Diagram of P-N Junction Diode

Because of movement of holes in the N-side and movement of electrons in the P-side an electric potential is formed near the junction. This electric potential is called junction potential or contact potential.

The formula for contact potential $V_0 = K_B T/e \times \ln(N_A N_D / n_i^2)$ [9]

Where K_B is Boltzman constant = 1.38×10^{-23} Joule/ Kelvin

T = 298°K at room temperature

N_A = Doping concentration at P-side

N_D = Doping concentration at N-side

n_i = Intrinsic carrier concentration

The formula for depletion region width $W_0 = [2\,\varepsilon\,(N_A + N_D)\,V_0 / e\,N_A N_D]^{1/2}$,

where ε is the permittivity of the semiconductor, e = charge of an electron and V_0 is the contact potential. The basic diagram of a forward biased P-N junction diode is shown in Fig. 8.

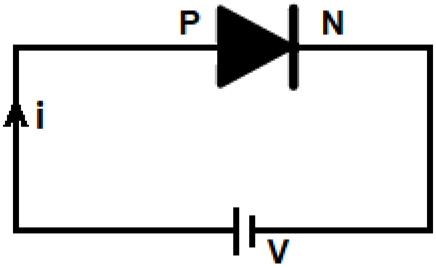

Figure 8 Diagram of a Forward Biased of P-N Junction Diode

The P-N Junction diode offers a low resistance when forward biased and offers a very high resistance when reversed biased. For this reason, diodes are basically used as a rectifier.

3.4. Full Wave Rectification using P-N Junction Diode

A full wave rectifier circuit using a centered tapped transformer consists of two diodes. The diodes are connected to the secondary coils of the transformer. A low ohm high watt resistor is used across the output and it is called a bleeder resistor as shown in Fig. 9. The function of this

bleeder resistor is to protect any surge voltage and when no-load current is drawn it becomes effective and acts as a load across the terminal.

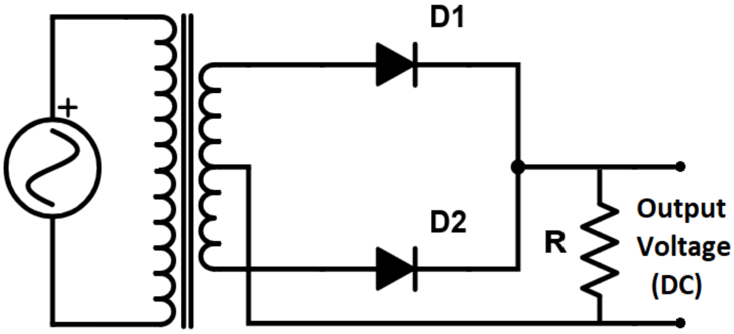

Figure 9 Diagram of Full wave Rectification using P-N Junction Diode

The average or DC value of this full wave rectifier is 0.636 **x** Peak Value [10]. This type of full wave rectifier is not used due to the ripple or pulsation in the output amplitude as shown in output waveform as shown in Fig. 10.

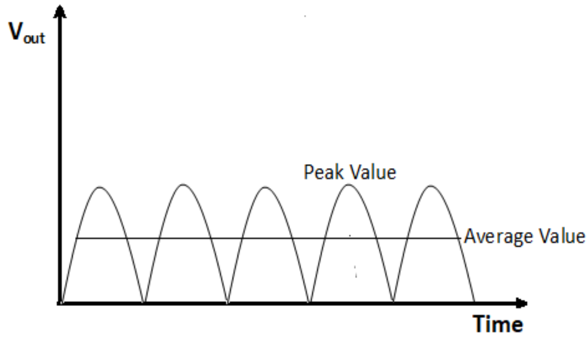

Figure 10 Output Waveform of Full Wave Rectifier

An electrolytic capacitor is used in parallel to the resistance as shown in Fig. 11. The bleeder resistor also helps the capacitor to discharge quickly when the power is off.

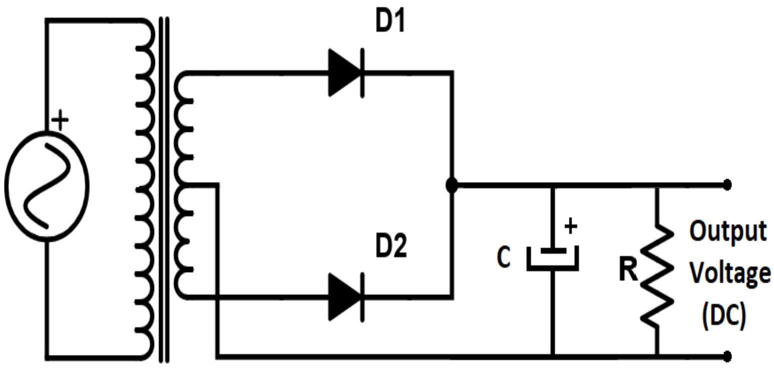

Figure 11 Full Wave Rectifier Circuit with Capacitance

The output of the full wave rectifier circuit is not pure D.C due to the ripple or pulsation in output amplitude. When a capacitor of sufficient large value is connected across the resistance in the output, then the output voltage approaches the peak voltage and the ripple is reduced to a large extent. When the rectified output voltage tends to fall, the capacitor supplies the energy stored in it during the charging period. So, the capacitor is able to provide the charge when the rectifier voltage tends to fall. Here the capacitor is not used as a voltage regulator. It is used for smoothing the output waveform as shown in Fig. 12.

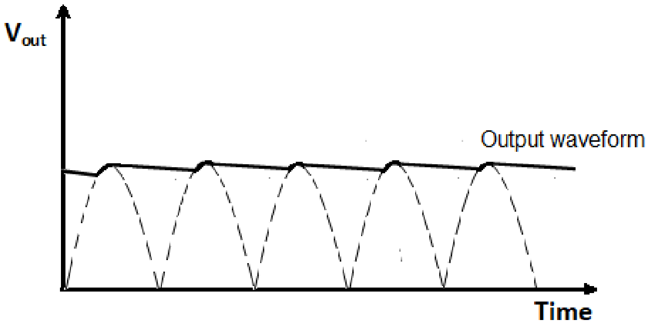

Figure 12 Output waveform of Full Wave Rectifier with Capacitance

When the capacitor is connected, output voltage approaches near the peak value. Further smoothing of output waveform can be done by using a low frequency choke-coil or an inductor as shown in Fig. 13. The choke-coil allows D.C. to pass through it but opposes A.C. pulsation. The existing ripples are further bypassed through the parallel capacitor C2 connected after the choke-coil. When another capacitor C1 is used before the choke-coil, the output voltage reaches towards the peak voltage of the A.C. pulsation and in this case the output voltage will be slightly greater than the choke-coil input filter circuit for the same input voltage [11].

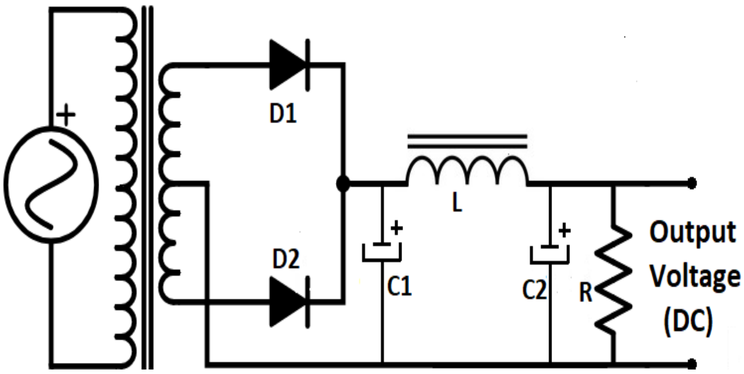

Figure 13 D.C. Power Supply Circuit with Choke-coil and Capacitance.

3.5. Invention of Transistor

The point-contact transistor was invented in the year 1947 at Bell Labs and then an improved bipolar junction transistor was developed in 1948. The commercial production of bipolar junction transistors was started in 1950 onwards. The invention of the transistor is a remarkable invention. The major uses of transistors were for the amplification of signals and very soon transistor replaced the triode valves. The other application of transistors is in the switching circuits and power supply regulation circuits.

The size of the transistor is very small and the cost is low. So, the size of a computer using transistors was reduced many times, power consumption was reduced and longevity was increased. When a computer made of valves occupied the space of a large room, a transistor-made computer with the same processing power can be kept on a small table. So, the transistor gradually replaced the valves and was used in the superheterodyne radio receivers, T.V. receivers, other consumer electronic products, scientific equipment and in industrial products.

4. REGULATION OF OUTPUT VOLTAGE

The zener diode came in the market in the year 1950 though working principle was theoretically described in the year 1934. Zener diode has a breakdown voltage and is used in the reverse biased mode. In the reverse biased mode the current flowing through the diode is very small

until it reaches the breakdown voltage. The current through the zener diode increases rapidly when the output voltage of the rectifier circuit tends to exceed the breakdown voltage. The application of zener diode as a simple voltage regulator is shown in Fig. 14. When the input voltage is sufficiently high than the output voltage, then power dissipation increases due to the junction breakdown of zener. Zener regulated power supply is used for low current power supply only.

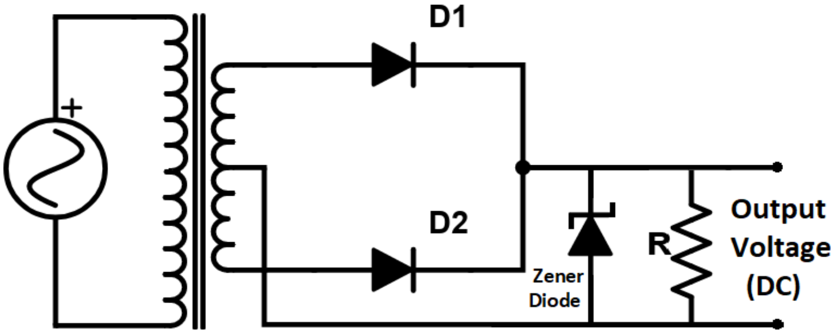

Figure 14 Power Supply regulation circuit with Zener Diode

4.1. Regulation of Output Voltage using Transistor and Zener Diode

The function of a voltage regulator is to maintain a constant output voltage depending upon load and some other parameters [12]. The voltage regulator circuit using a zener and a transistor is shown in Fig. 15. Here a zener stabilized voltage is applied to the base of the transistor. The transistor acts as an emitter follower and can deliver a large amount of current in comparison to only zener regulated current. For the further requirement of excessive current, another transistor can be connected as Darlington Pair.

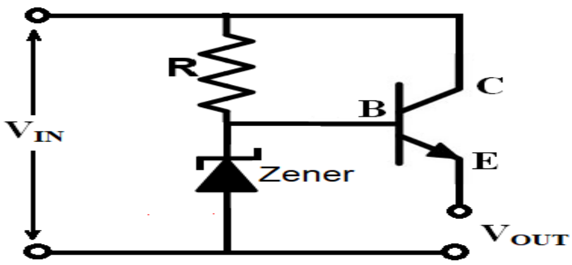

Figure 15 Voltage Regulator Circuit using a Zener and Transistor

4.2. Simple Buck (Step Down) Switch Regulator

Buck regulator takes input power from the D.C power supply and by controlling the 'ON' period and 'OFF' period of the switch, the desired output voltage can be obtained as shown in Fig. 16. In the buck regulator, the input D.C voltage should be higher than the regulated output voltage. Since the input voltage to be higher than the output voltage that is why it is also called buck converter.

The output voltage (V_{OUT}) = (T_{ON} x V_{IN}) / (T_{ON} + T_{OFF}) [13]

Here T_{ON} = on period of the switch

T_{OFF} = off period of the switch

V_{IN} = Input voltage of the switch

For 50% duty cycle, output voltage will be reduced to half of the input voltage. For 25% duty cycle output voltage will be reduced to one-fourth of the input voltage and so on.

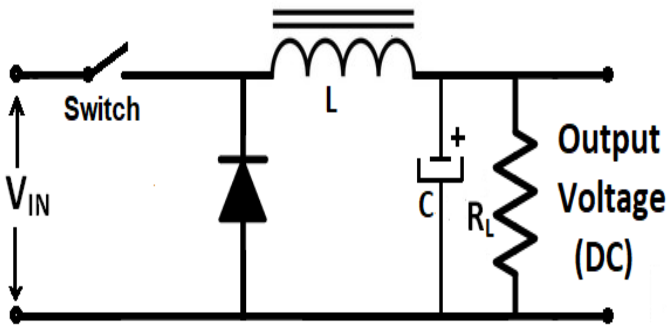

Figure 16 Basic Diagram of a Buck Regulator

4.3. Buck Voltage Regulator with Pulse Width Modulator

The control circuit of a voltage regulator uses a comparator and error amplifier. When there is a variation of output voltage, the comparator detects this variation and this variation is corrected by an error amplifier in the pulse width modulator (PWM) circuit [14]. The chip UC 3578 can be used as a PWM converter and error amplifier.

As shown in Fig. 17, when the transistor (BJT or MOSFET) is turned 'ON', the diode becomes reverse biased and the current flows to the connected load in the output and also the capacitor is charged. As the current flows through the inductance, the coil opposes any change in the magnetic field by generating an back e.m.f until the magnetic field reaches a steady state around the inductance during the 'ON' state of the transistor [15].

When the transistor is turned 'OFF', the magnetic field around the inductor collapses and reverse voltage is induced across the inductor. In this situation, the energy stored in the inductor is supplied to the load in the same direction. During this 'OFF' state of the transistor, the diode becomes forward biased and the current returns back through the diode [16]. The buck converter is a type of switch mode power supply where switching of transistor occurs at a very high speed in the range of several KHz to several hundred KHz.

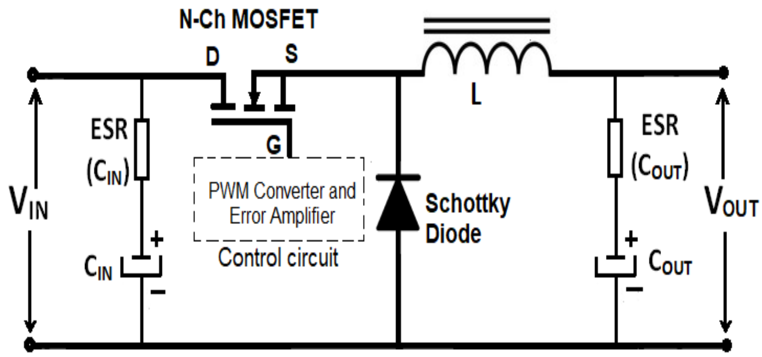

Figure 17 Buck Regulator with N-Channel MOSFET

4.4. Low Dropout Regulator (LDO)

In the low dropout voltage regulator output voltage is also lower than the input voltage like a buck converter. Drop voltage between input and output is maintained as small as possible in a low dropout voltage regulator. When the drop voltage between input and output will be large, then power dissipation across the low dropout regulator will be more and proper heat sink to be used. Buck converter is a type of switch mode power supply where a transistor is switched 'ON' and switched 'OFF' at a very high rate [17]. But in the low dropout voltage regulator, the transistor operates in the linear region and is used when the voltage drop between input and

output is small. Nowadays many communication devices like Wi-Fi, ZigBee, Z-Wave, BLE, LoRa, LTE, NBIoT etc. consume very low power. So, low dropout regulators can be suitable for these low power devices.

The basic diagram of a low dropout regulator is shown in Fig. 18. The desired output voltage can be obtained using the feedback voltage which is applied to the non-inverting input of the error amplifier from the junction of R_1 and R_2 [18]. The error amplifier drives the gate to source voltage (V_{GS}) of the MOSFET. More negative V_{GS} will lower the resistance between drain and source (R_{DS}) until saturated [19].

The dropout voltage = R_{DS} x I_{LOAD}

Power dissipation in LDO can be calculated as $P_D = (V_{IN} - V_{OUT}) \times I_{LOAD}$

Quiescent current (I_Q) of LDO is very low and in the range of a few µA. Quiescent current is consumed by the LDO during its active function.

Two types of LDOs are used based on P-channel and N-channel MOSFET. For the input voltage greater than 2.5V and generally in the range 3V-5V, PMOS type LDO is used. For the input voltage of about 1V, NMOS type LDO is used.

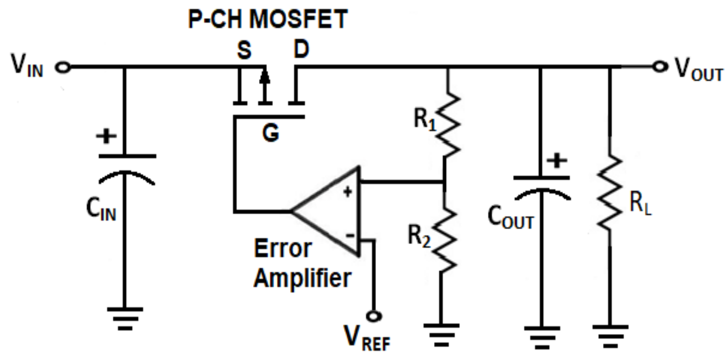

Figure 18 Diagram of Low Dropout Regulator

5. AMBIENT ENERGY HARVESTING SYSTEM

In the ambient energy harvesting system, ambient energy sources like electromagnetic energy, thermionic energy, piezoelectric energy, solar energy etc. are used to produce electrical energy. Even energy from the human organs such as electrical stimulus generated by the SA node from the human heart can also be used as harvested energy. The energy harvesting system does not require any external power supply.

5.1. Solar Energy Harvesting System

Solar energy systems are gradually becoming alternating sources of conventional energy due to its abundant natural resources and available moderate technology. A solar cell is a photovoltaic cell and can produce electrical current when the solar cell is exposed to sunlight. When photon energy (E) of the solar cell (equal to $h\nu = hc/\lambda$) is greater than the band gap (E_g) of the semiconductor and is incident on a semiconductor then excess radiation energy ($E - E_g$) is absorbed by the semiconductor lattice. This absorption produces electrons in the conduction band and holes in the valence band.

A simple solar cell is made up of P-type and N-type silicon. Silicon is processed from silicon dioxide (SiO_2) using Czochralski technique or Float-zone technique. Silicon boules are made in the clean room environment and its purity depends upon the classes of clean room starting from class 1 to class 100,000. When silicon boules are produced in the class 1 environment, its

purity is close to 100 percent. Silicon wafer is always oriented to n-type 110,111,100 and p-type 110,111,100 and this orientation is defined by Miller Index.

5.1.1. Solar Spectrum

The solar spectrum consists of ultraviolet rays (100-400nm), visible light (400-780nm) and infrared radiation (780-2500nm). Oxygen molecules in the stratosphere absorb more than 99 percent UV-C rays and the ozone layer of the stratosphere absorbs about 90 percent of UV-B radiation. The ozone layer also absorbs about 50 percent of UV-A radiation. Solar radiation that reaches the earth mainly consists of 6.6% ultraviolet radiation, 44.7% visible radiation and 48.7% infrared radiation [20][21].

It is found that visible light of wavelength around 500 nm reaches the earth with the most intensity [22].

5.1.2. P-N Junction Solar Cell

Here dopant concentration of the N- region is higher than the dopant concentration of the P-region and for this reason depletion width in the N-side is narrower than the depletion width of P-side as shown in Fig. 19.

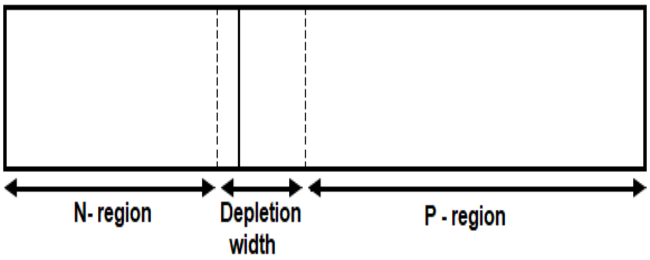

Figure 19 P-N Junction with higher Dopant Concentration in N-side

Solar radiation of shorter wavelengths has higher photon energy and is absorbed near the surface of the solar cell. Solar radiation of larger wavelengths can reach the P-region of the solar cell through N-region when solar radiation is exposed to the N-region of a P-N junction solar cell. Penetration of radiation depends on the wavelength of the incident radiation and the absorption coefficient is higher for shorter wavelength as shown in Fig. 20.

According to the nature of wavelengths, electron-hole pairs are generated at different regions and electrons move to the N-region and holes move to the P-region [23]. As long as solar radiation is exposed to the solar cell electrons and holes from the generated electron-hole pairs move to the N-region and P-region correspondingly and behave like a battery.

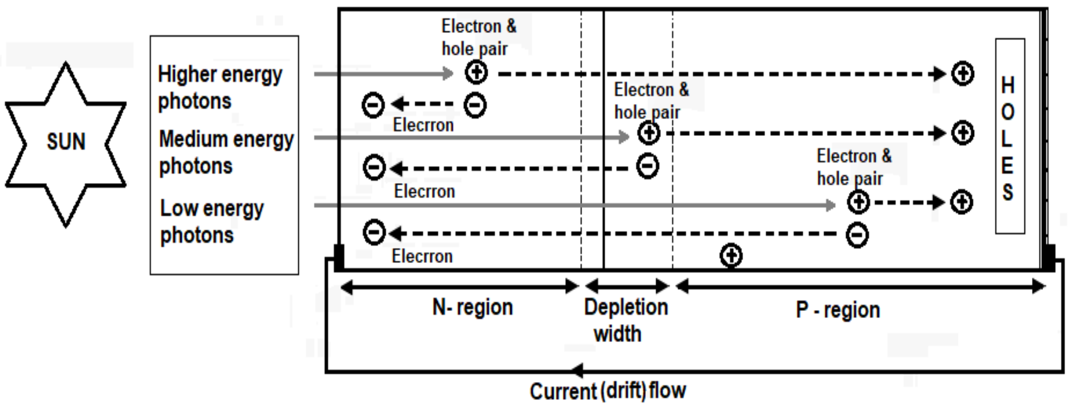

Figure 20 Silicon (λ=1.11eV) based P-N Junction Solar Cell

For better understanding of the penetration depth of various wavelengths, we can calculate the photon energy of various wavelengths using the formula

$E = \frac{hc}{\lambda} = \frac{6.626\times10^{-34} \times 3\times10^{8}}{400\times10^{-9} \times 1.6\times10^{-19}}$ eV, where E is photon energy, h is Plank's constant, c is speed of light and λ is the wavelength.

Table 2 Photon Energy verses Wavelengths

Wavelength(λ) in nanometer	**Energy (E)** $= \frac{hc}{\lambda} = \frac{6.626\times10^{-34} \times 3\times10^{8}}{400\times10^{-9} \times 1.6\times10^{-19}}$ **eV**
400 nm	3.106 eV
450 nm	2.761 eV
500 nm	2.485 eV
550 nm	2.259 eV
600 nm	2.071 eV
650 nm	1.911 eV
700 nm	1.775 eV
800 nm	1.553 eV
900 nm	1.380 eV
1000 nm	1.242 eV
1100 nm	1.129 eV
1200 nm	1.035 eV
1300 nm	0.956 eV
1400 nm	0.887 eV
1500 nm	0.828 eV

Electron and hole pairs are generated due to solar radiation, and the photo current (I_{ph}) generated from these electron and hole pairs is drift current and its direction is shown in Fig. 21. Also due to the creation of P-N junction where holes diffuse to N-region and electrons diffuse to P-region another current is generated which is called diffusion current (I_{dh}). The direction of the diffusion current is opposite to the direction of the drift current.

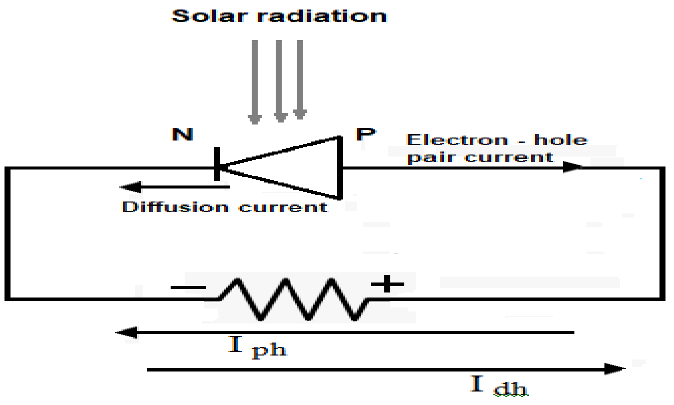

Figure 21 Current flow in Solar Cell is shown in diagram

The net current available from the solar cell can be written as

$I = I_d - I_{ph}$ [23]

$I = I_{SO}\ [\ e^{\frac{eV}{KT}} - 1] - I_{ph}$, where I_{SO} is reverse saturation current

5.2. Piezoelectric Energy Harvesting

The key component of the piezoelectric energy harvesting system is a quartz crystal which acts as an energy converter. The quartz is a crystalline mineral and is composed of silica which is an oxide of silicon dioxide. The piezoelectric effect of a quartz crystal generates electrical signal when the surface of the quartz crystal is subjected to mechanical stress or vibration. The reverse property is also true for the piezoelectric quartz crystal i.e. when electrical signal is applied to the surface of a crystal, the vibration is produced in the crystal [24] [25]. The basic symbol of a piezoelectric crystal is shown in Fig. 22.

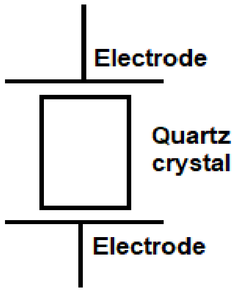

Figure 22 Symbol of a Quartz Crystal

The generated energy of the piezoelectric transducer depends on the speed and magnitude of the stress applied on the surface of the quartz crystal. The generated energy is rectified using the rectifier circuit and stored in the energy storage device. A simple diagram with bridge rectifier circuit is shown in Fig. 23.

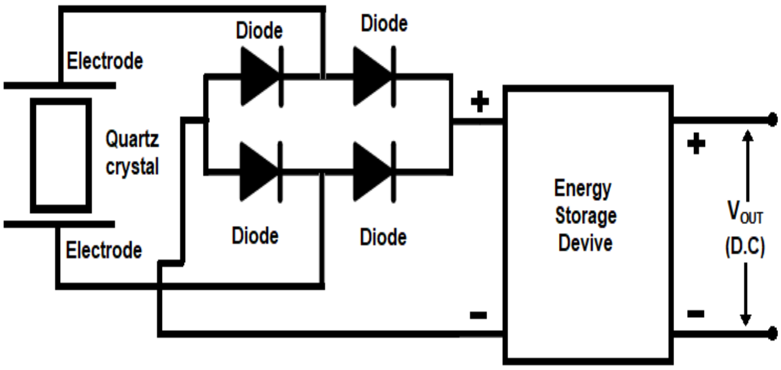

Figure 23 Diagram of Piezoelectric Energy Harvesting System

5.3. Energy Harvesting from Human Organ

Various types of electrical signals are generated from the human body such as EMG signal, EEG signal, ECG signal etc. Among these signals, the ECG signal is strongest in amplitude at the level of millivolt and is produced in the sinoatrial (SA) node of the human heart [26] [27]. ECG signal is a cardiac signal and its electrical representation can be understood from Einthoven's Triangle as shown in Fig. 24. Einthoven's triangle is described by the three bipolar leads. Lead-I is connected between the left arm and the right arm. Lead-II is connected between the left leg and right arm. Lead III is connected between the left leg and left arm [28]. The amplitude of cardiac signal in a specific lead depends on the orientation of the axis of the heart. The ideal axis of the heart is 45° but a wide range of deviation between – 30°to +90° is accepted as the normal axis of the heart. When the axis is more or less 45°, then the highest amplitude is available in the lead-II because lead II is almost parallel with the axis of the heart. The Amplitude of lead-III is lowest because lead-III is least parallel with the axis of the heart.

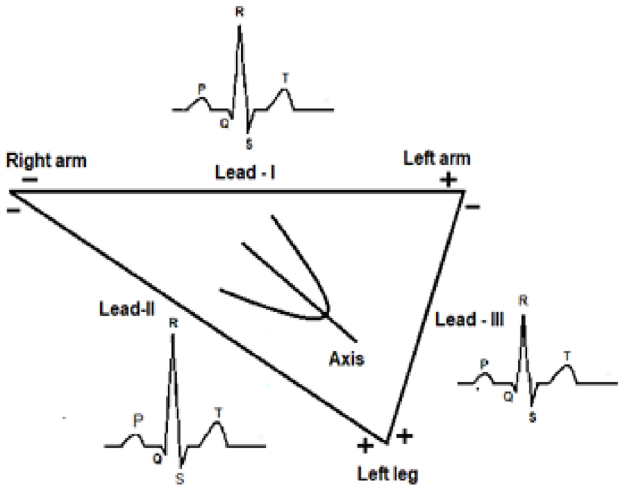

Figure 24 Einthoven's Triangle with waveforms for Lead-I, II and III

The waveform of a single heart beat is shown in Fig. 25. The waveform consists of P-wave, Q-wave, S-wave, QRS-complex, S-T segment and T-wave. After the T-wave, sometimes less important another wave called U wave is available before the P-wave of the next cycle [29].

The point R is called R-wave and its amplitude is the highest. Normally in lead-II, the amplitude of R-wave is 01 mv. This amplitude is available during the depolarization of the ventricles [30]. The duration of a heart beat depends on the number of beats occurring in a minute. The heart beat 60 to 100 is accepted as a normal heart beat for adults.

When the heart beat is 72/minute, then the duration of a cardiac cycle = $\frac{60}{72}$ = 0.833 seconds.

When the heart beat is 60/minute, then the duration of a cardiac cycle = $\frac{60}{60}$ = 01 second.

When the heart beat is 100/minute, then the duration of a cardiac cycle = $\frac{60}{100}$ = 0.6 seconds.

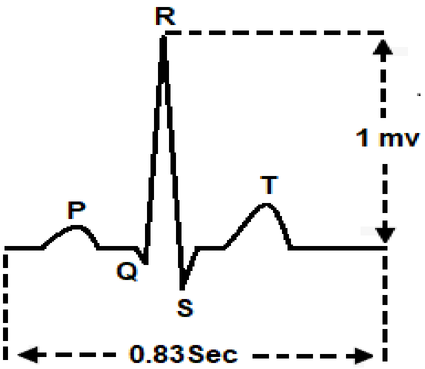

Figure 25 Waveform of a Cardiac Cycle for heart beat 72/minut**e**

6. CONCLUSION

Electricity can also be produced using the Seebeck effect. In the Seebeck effect, the current is produced at the junction of two dissimilar metals when one end is hot and the other end is kept cold. The scope of the generation of electricity using the Seebeck effect is impractical due to its inefficiency. The electricity is also harvested from wind energy but wind energy is mostly seasonal. There is also a big scope for harvesting energy from tidal energy with anticipated power. Besides, various types of ambient low power energy are available like electromagnetic energy, electrostatic energy etc. Future research will predict more feasible and environment-friendly energy harvesting systems.

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